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Estimating the Impact of Crashworthiness Standards on Mortality and Morbidity Events in U.S. Army Rotary-wing Aircraft Mishaps

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It is generally agreed that it is desirable to provide modern military helicopters with the maximum crashworthiness practical in order to reduce injury in helicopter crashes. Although crashworthy design features have been proven to be extremely effective in reducing morbidity and mortality, a penalty of increased weight and added procurement cost must be paid. Consequently, the degree of crashworthiness designed into an aircraft must be a tradeoff between economics, aircraft performance, and the perceived risk of injury. To help these judgments, it would be useful to develop a mathematical model capable of predicting morbidity outcomes for a given aircraft design. All crashes of five types of U. S. Army helicopters occurring between 1 October 1979 and 30 September 1991 were examined to determine crash conditions and morbidity and mortality outcomes. Analyses were conducted with logistic regression (LOGISTIC) for mortality and the fit of the model was considered. Helicopters were coded as crashworthy or precrashworthy based

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upon whether they were designed to current U.S. Army crashworthiness standards. Prevalence figures are presented with odds ratios that signify the odds of fatal injury in a crashworthy helicopter relative to the odds of fatal injury in a pre-crashworthy helicopter. Results showed a significant increase in mortality for pre-crashworthy helicopters for similar impact conditions. The model predicts incremental increases in mortality associated with reducing the vertical velocity design standard for existing helicopters. When applied to estimating the increased injury associated with decreasing the vertical velocity design standard from 38 to 32 ft/s for a developmental helicopter, the RAH-66 Comanche, the model predicted a 7.7 percent increase in mortality.

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Introduction

There is a growing consensus that incorporating crashworthiness features into U.S. Army helicopters is both desirable and cost effective, but there is also increasing debate about how much crashworthiness is appropriate considering current fiscal realities. Whether more aggressive and costly standards truly result in significantly higher survival among aircrews and, if so, to what degree has not been well documented. The AH-64 Apache and UH-60 Black Hawk were the first U.S. Army helicopters designed to modern crashworthiness standards, and generally have proven themselves to be extremely crash survivable in comparison to their predecessors (Shanahan and Shanahan, 1989b). Current U.S. Army crashworthiness standards were adopted to maximize the likelihood of occupant survival, within practical constraints, in potentially survivable crashes. The effectiveness of these standards in reducing the likelihood of injury versus their costs has provoked considerable controversy as to the future course of rotary-wing aircraft design both for military and civil uses. The present study addresses this issue by developing a model capable of predicting the effect of varying crashworthiness design standards on mortality outcomes in crashes of Army helicopters.

Economic pressures, many associated with the reduction in U.S. military forces, have caused Army helicopter developers to reduce crashworthiness standards in an effort to reduce the procurement costs of new models. These pressures have been particularly intense in the development of the RAH-66 Comanche, the Army's newest reconnaissance/attack helicopter. Over the course of the Comanche's development, certain crashworthiness standards have been reduced repeatedly in an effort to reduce weight and procurement costs while preserving total mission capability. The implementation of these cost-saving strategies during the development process has increased the need for robust and flexible models capable of predicting the probability of injury for rotary-wing occupants under a variety of crash scenarios for different crashworthiness design parameters. Such models would provide program managers with a means of assessing accurately, in terms of morbidity and/or mortality outcomes, the effect of contemplated design changes. Utilizing such comparisons, program managers would have an objective measure on which to base crashworthiness design tradeoff decisions early in the development cycle.

Materials and methods

The Army Safety Management Information System (ASMIS), a computerized database maintained by the U.S. Army Safety Center (USASC) at Fort Rucker, Alabama, contains historical information

on all Army aircraft mishaps since 1971. Mishaps involving U.S. Army aircraft are investigated by an appointed Accident Investigation Board (AIB) and the board's findings are recorded on DA Form 2397, a standardized aircraft mishap reporting form. After completion, the AIB submits all DA Forms 2397 to the USASC where they are reviewed, coded, and keyed into the ASMIS database.

Data on all U.S. Army class A and B mishaps which occurred during the period 1 October 1979 to 30 September 1991 were reviewed. Class A mishaps are defined by regulation (AR 385-40) as mishaps for which the resulting total cost of property damage, occupational illness, or injury is $1,000,000 or greater, or in which an injury results in a fatality or permanent total disability. Class B mishaps are defined as mishaps for which the total cost is greater than $500,000 but less than $1,000,000. Other classes were not included in the study since they usually did not involve significant impact or result in injuries. Besides the class requirement, eligibility for the study required the mishap have a ground-strike (GS) component (defined as a vertical velocity change greater than zero). Also, mishaps occurring during ground taxiing, in-flight wire or other obstacle strikes for which the helicopter subsequently landed safely, and mishaps where personnel fell from helicopters or were struck by moving helicopters or rotor systems were excluded.

Although the Army operated many types of rotary-wing aircraft during the study period, only five helicopter types were included in this study: the AH-1 Cobra, AH-64 Apache, OH-58 Kiowa, UH-1 Iroquois, and UH-60 Black Hawk series. Of the helicopters excluded, the majority were cargo helicopters (CH-47 and CH-54 series) and certain special operations helicopters which differ markedly in size, aerodynamics, or typical operational missions from the helicopters included in the study.

This study was designed to address three issues regarding the crashworthiness of U.S. Army helicopters. First, helicopter series were compared to determine if specific helicopter types suffered more crashes than others. Second, injury data were examined to determine if aggressive design strategies in newer helicopter series had resulted in significantly reduced injury rates. Finally, injury risk for crewmembers was compared to determine whether differences in crashworthiness standards modified the injury risk.

Injury analyses were restricted to cockpit crewmembers. This maximized comparability across helicopter types since attack and observation helicopters usually had two crewmembers, whereas utility helicopters carried cockpit crew and up to 20 passengers. Furthermore, restraint systems and protective equipment (helmets, fire-retardant flight suits) for cockpit crew generally are standardized across helicopter types. Other occupants wear a

variety of protective equipment and, in certain helicopters, simply sit, unrestrained, on the floor of the helicopter during flight. Limiting the analyses to cockpit crewmembers greatly simplified analysis, eliminating several extraneous factors in the modeling process.

In injury research, the parameters of occurrence, such as the incidence of a particular injury, are not viewed as a constant of nature. Rather, their magnitudes generally depend on or are a function of a variety of characteristics such as impact dynamics, individual anthropometry, postimpact events (such as fire) and impact terrain. To say that a characteristic of a crash has an effect on some aspect of injury means there are instances in which the status of the characteristic makes a difference in the subsequent course of events. Such characteristics are called "determinants."

Other factors, called "modifiers," have an effect on some aspect of the relationship between the occurrence rate and the determinant. Consider the effect of fire on the likelihood of crewmember mortality. There are instances of a crewmember being "saved" in an aircraft fire by flame retardant clothing, and there are instances of fire deaths in flame retardant clothing. The survival effect of flame retardant clothing (for that aircraft series) would be characterized properly in terms of the relative frequency of each outcome. In this case, fire is a powerful determinant of crewmember death and flame retardant clothing is a modifier of fire since the outcome would have been unaffected by type of clothing material in the absence of fire.

Determinants relating to injury in helicopter crashes have been recognized for years (Aircraft Crash Survival Guide, 1989). Indeed, there is considerable understanding of the distinct roles of various kinematic parameters in the etiology of injury. The existence and even the nature of modifiers sometimes can be surmised in general terms. Consider, for example, the relationship of the incidence of cyclic injuries to vertical velocity change, as modified by cyclic design. One would expect that improving the cyclic design would reduce the injury risk, that is, the risk of cyclic injury at a given velocity. This means, in turn, that any difference in risk of injury at a given velocity is the result of the modifier. The concept of modifiers in the context of injury determinants is essential to our discussion of helicopter design criteria.

Despite the appeal of determinants and modifiers, most investigations of injury have employed multiple regression functions whose constituent variables were defined without reference to a mechanistic theory. This approach arbitrarily assumes that the combined effects of the defined variables are multiplicative. The multiplicity of possible relations between design-specific

injury incidence rates and two or more velocity-related predictive characteristics suggest reference to a bioengineering theory of injury for guidance in quantifying the combined effects.

Our approach to analyzing the ASMIS data is described more fully elsewhere (Appendix A). In brief, we observed that the bulk of the injuries occur in the extremely long, nongaussian right tail of each kinematic distribution. This suggests the likelihood of injury is not a random event and could be predicted with some degree of certainty. Reflecting the combined effect of helicopter design (modifier) and the crash kinematics (determinant), our analytical theory assumes that reducing injury risk requires two transitions. In the first transition, the probability of injury is zero before a kinematic threshold and constant thereafter. The second transition (from the initial state based on the helicopter design) generates an injury probability that is dependent upon the energy of the crash. Whether or not certain design-related factors were predictive of higher injury risk was explored utilizing this analytical framework.

Specific ASMIS variables of interest to this study included: helicopter identifiers (helicopter series and tail number), mission history (date, number of occupants, mission, and flight duration), mishap specific information (class, survivability, terrain descriptors, obstacle impacts, etc.), kinematic estimates (roll, pitch, yaw, vertical velocity, and ground speed), and crewmember specific data fields (demographics, injury descriptors, injury causation factors, etc.).

To perform statistical analyses to estimate the relative risk of injury, the ASMIS variable, DEGINJ (degree of injury), was recoded into three binomial variables: fatal (I_1), major (I_2), and minor (I_3) (Table 1). The distinction between major and minor injury was made based on the criteria established in DA PAM 385-95 (1983).

Table 1.

Injury coding schema (I_1-I_3) according to DEGINJ.

Degree of injury (DEGINJ)		I_1	I_2	I_3
A	Fatal injury	1	0	0
B	Permanent total disability	0	1	0
C	Permanent partial disability	0	1	0
D	Lost workdays	0	0	1
E	Lost workdays: restricted duty only	0	0	1
F	Injury: without lost workdays	0	0	0
G	First aid only	0	0	0
H	Missing and presumed dead	1	0	0
.	Missing: presumed no injury	0	0	0

To maximize the probability of survival or, in the sense being discussed, to minimize the likelihood of injury, it is important to understand the determinants and modifiers of injury in a helicopter crash. This is because changes in such factors markedly effect an aviator's lifetime risk of injury. When a helicopter impacts the ground, three factors appear to have overriding influence on the probability of injury: the dynamics of the impact, various helicopter structural design parameters, and the physical characteristics of the crash site.

Comparisons, using historical data, have found strong correlations between impact velocity change and injury risk. The strongest correlation is associated with vertical velocity change at primary impact (Shanahan and Shanahan, 1989a, b). Consequently, the tolerance of any helicopter to vertical impact is linked to decreased injury risk. Considering vertical velocity alone, one would hypothesize a threshold below which crewmembers in a particular helicopter series would not be injured significantly. Of the five helicopter types considered in this study, only the AH-64 and UH-60 were designed and tested to a specific vertical velocity impact standard. This was 38 ft/s for the UH-60 and 42 ft/s for the AH-64.

A study by Shanahan and Shannon (1993) validated the Army's injury threshold estimate for the AH-64 and UH-60 using the ASMIS database, and provided threshold estimates for the AH-1, OH-58, and UH-1 helicopters. In this study, the authors estimated the

threshold for lost workday injury was 13 ft/s for the AH-1, OH-58, and UH-1 in essentially vertical crashes. A lost workday injury was defined as an injury which resulted in at least one lost workday. An essentially vertical was defined as a crash with a roll angle of less than 45 degrees, a pitch angle greater than -15 or less than 25 degrees, and a yaw angle of less than 45 degrees. Last, a threshold was defined as the level at which the likelihood of injury exceeded 0.5.

The model

This section contains a mathematical description of the injury incidence rate function. It depends on several unknown parameters, and provides a general framework for fitting an injury model to the ASMIS data.

To provide a starting point, we will show that our model gives rise to a multinomial distribution for the observations, with probabilities that condition on the kinematic parameters of the mishap. We then show that these conditional probabilities can be written as functions of the desired marginal probabilities, which leads to straightforward estimates of the parameters of the marginal distribution through the likelihood function.

Suppose injury data are collected in a retrospective study in which *(i.)* helicopter mishaps occur randomly from a population of aircraft; *(ii.)* crewmembers are assigned randomly to specific helicopters; *(iii.)* at baseline, crewmembers are free of the event in question; *(iv.)* all crewmembers are examined after the mishap; *(v.)* each crewmember's vector of observations is complete; and *(vi.)* there are no competing risks. The assumption that crewmembers are a random sample from the aviator population allows generalization of the results from the study to that population. Assumptions *iv* and *v* ease the estimation problem and the notation, but they are not critical to the model.

The basic mathematical model will be discussed in terms of the probability that the event of interest has occurred by a given velocity,

$$p\{y(v) = 1 \mid x, \phi)\} \tag{1}$$

where $y(v)$ is a binary indicator that the event has occurred by velocity v, X is a vector of covariates, and ϕ is a vector of parameters.

To establish notation, let $y_i(v_j)$ be a binary indicator such that $y_i(v_j)=1$ if the event has occurred in the i^{th} individual $(i=1,\ldots\ldots,N)$ by j^{th} velocity $(j=0,\ldots\ldots,J)$, where v_j is estimated

vertical velocity for this mishap, and N is the sample size. Let x_i be a vector of covariates for the i^{th} subject.

Define $y_i(v_0)$ to be the indicator of status at baseline. By assumption iii, $y_i(v_0)=0$ for all subjects. Let x_i be a vector of covariates for the i^{th} subject. In these definitions, subscripts i and j are employed to denote observations, as opposed to random variables. Thus, $y(v)$ is a random variable and $y_i(v_j)$ is an observed value for it. Where necessary, we also use $y(v_j)$ to denote a random variable at observed velocity v_j. It should be clear that we want to estimate the distribution of $y(v)$ using $y_i(v_j)$.

To simplify the initial modeling, assume that x_i does not vary among subjects or, equivalently, that the covariates (including crashworthiness) are not included in the model. Then under assumptions i-iv, the data can be represented as a collection of samples from independent multinomial distributions, one for each vertical velocity. That is, let $c(v_o)$ be a K-dimensional vector of counts (K=J+1),

$$C(v_o)^D = \{c_1(v_o), \ldots\ldots, c_k(v_o)\}$$

such that, if $1<=k<=J$, $c_k(v_o)$ is the count of those who first display the event of interest at the k^{th} velocity and $c_K(v_o)$ is the count of those still free of this event at the highest observed velocity. Then $C(v_o)$ is the vector of multinominal counts. Owing to assumption iii, the probabilities for this multinominal must condition on baseline status. Thus, the expected values for the first K-1 terms in $C(v_o)$ are

$$E\{c_k(v_o)\} =$$

$$N(v_o)p\{y(v_{j'})=0,\ y(v_j)=1 \mid y(v_o)=0,\ Z^*\} \qquad (2)$$

where $j'=j-1$, $k=j$ and Z^* is a vector of parameters. The probability in (2) is the probability that the event occurs between velocity j' and j, given that it had not occurred by baseline. The expected value for the K^{th} count is

$$E\{c_k(v_o)\} =$$

$$N(v_o)p\{y(v_j)=0 \mid y(v_o)=0\ Z^*\} \qquad (3)$$

The probability in this expression is the probability that the event of interest does not occur within the mishap parameters observed during the study, given that it had not occurred by baseline. The conditional probabilities in (2) and (3) are easily rewritten as functions of the marginal probabilities.

From (2),

$$p\{y(v_j) = 0,\ y(v_j)=1 \mid y(v_o)=0,\ Z^*\} =$$

$$[p\{y(v_j)=1 \mid Z\} - p\{y(v_j)=1 \mid Z\}] \,/\, p\{y(v_o)=0 \mid Z\} \tag{4}$$

where Z is the parameter vector for the marginal distribution.

The probability in (3) takes on a slightly different form:

$$p\{y(v_j)=\text{zero} \mid y(v_o)=0,\ Z^*\} =$$

$$p\{y(v_j)=0 \mid Z\} / \, p\{y(v_o)=0 \mid Z\} \tag{5}$$

Expressions (4) and (5) provide the desired result: the probabilities in (2) and (3) are expressed as functions of the marginal distribution. As a result, estimations of the parameters of the multinomial distribution provide estimates of the parameters of the marginal distribution. We need only to specify a form for the marginal probabilities, the choice of which will vary from parameter to parameter. We chose to utilize logistic regression (Hosmer and Lemeshow, 1989):

$$p\{y(s)=1 \mid Z\} =$$

$$[1 + \exp\{-(Z_1+Z_2 v)\}]^{-1} \tag{6}$$

where

$$Z^V = (Z_1,\ Z_2)$$

Substitution of (6) into (4) and (5), with observed values for velocity, gives a means of estimating the parameters of the marginal distribution from the data obtained from the ASMIS database.

An important feature of (6) is that this probability does not condition on baseline velocity. Since we assume there is a cohort effect, i.e., the form of the marginal distribution varies with different levels of crashworthiness design, then Z could be estimated separately for each design standard or indicator variables for each design standard to X, with corresponding parameters added to Z* and Z. Similarly, if we assume there is a cohort effect for kinematic parameters other than vertical velocity, we can add these to the model. (Kalbfleish and Street, 1990, provide an excellent discussion of logistic regression modeling.)

A threshold effect is an association between a risk factor and a defined outcome that is observable above the threshold

value but not below it. When the injury function is plotted on a log-log scale with vertical velocity at major ground-strike, it has a slope that changes after certain events. The mathematical aspects of the concept of thresholds are described by Draper and Smith (1966). From a statistical point of view, the question is whether one or two segmented regression lines are appropriate, and, in the case of two segmented regression lines, the location of the change point. Most of the approaches to this problem are based on ordinary least squares (continuous dependent variable) or maximum likelihood (dichotomous dependent variable). In this paper, we test the hypotheses of threshold effect within the framework of logistic regression. To estimate the threshold for a risk factor we proposed the following model:

$$\text{logit } P(x) = \ln (P(x) / (1-P(x)) = \beta_0 + \beta_1 x, \qquad (7)$$

where $P(x)=P(Y=1|X=x)$ and β_0 and β_1 are constants.

To test if the explanatory variable x has a threshold, denoted by τ, (7) is modified to:

$$\text{logit } P(x) = \begin{cases} \beta_0 & \text{for } x \le \tau \\ \beta_0 + \beta_1(x-\tau) & \text{for } x > \tau \end{cases}$$

which is equivalently,

$$\text{logit } P(x) = \beta_0 + \beta_1(x-\tau)I + (z)$$

$$\text{with } I+(z) = 0 \text{ for}(x - \tau \le 0) \text{ and } 1 \text{ for } (x-\tau > 0) \qquad (8)$$

To estimate the parameters β_0, β_1, and τ of the model (8), the likelihood function $L(\beta_0, \beta_1, \tau)$ is maximized.

$$LL(\beta_0,\beta_1,\tau) = \ln LL(\beta_0,\beta_1,\tau) = \Sigma\ [\delta_j \ln(P(x_j)) + (1-\delta_j) \ln(1-P(x_j))] \qquad (9)$$

where d_j = 0 if subject j had no event and 1 if subject j had the event.

The threshold cannot be estimated directly from available statistical packages; however, following an approach by Hosmer and Lemeshow (1989), if we iterally increased the value of τ so that when $LL_j(\beta_0,\beta_1,\tau^j)$ $\iota\sigma\ \tau\eta\epsilon$ was maximum, then τ was known to be between $\tau^{(j-1)}$ and $\tau^{(j+1)}$. When no maximum was found, the explanatory variable was said to have shown no single threshold point.

In this paper, maximum likelihood estimates from logistic regression modeling were used to study the threshold effects for explanatory variables such as roll, pitch, and horizontal

velocity. Model (8) can be expanded to more than one explanatory variable, and more than one variable with a threshold.

Statistical analyses

To examine time trends in risk factors in mishaps across helicopter type, we examined data stratified by fiscal year. To test for significant time trends in risk factors, we employed analysis of variance (ANOVA), multiple linear regression models for kinematic factors, and a logistic regression model for mortality. The nonsignificance of time and first-order interactions of time x planned flight duration, crewmember age in years x time, helicopter type x crewmember age in years simplified our analyses.

Since we hypothesized there would be increases in helicopter flight performance over time, we included kinematic parameters as a continuous variable to test for linear trends. We included helicopter series as a covariate in all models because certain helicopter series tended to crash at higher vertical and horizontal velocities than other series (Shanahan and Shanahan, 1989a). Vertical and horizontal velocities were transformed to their squared values since energy is expressed in terms of mass x squared velocity. In the estimates of the relative risks for specific crashworthiness standards, we adjusted the logistic regression model for roll and pitch. This adjustment was made because the current crashworthiness standard, MIL-STD-1290, limits roll and pitch angles when defining the vertical velocity change impact standard.

While most analyses were carried out in SAS® (1990), a statistical package developed by the SAS Institute, Cary, North Carolina, exact analyses of multiple 2x2 tables with sparse data were performed utilizing the method proposed by Fleiss (1979), and Mehta, Patal, and Gray (1985). All p values presented from multiple linear and logistic models are two-tailed.

Results

Our most elementary level of modeling the occurrence of injury was a qualitative one. On this level, the question was whether there was an unconditional (crude) relationship between the occurrence of injury and a potential determinant. At the next level of modeling, we were concerned with the existence of an association conditional on some other determinants, but still in the framework of purely descriptive relations. Finally, we were concerned with identifying any causal relationships.

Five helicopter types -- AH-1 Cobra, AH-64 Apache, OH-58 Kiowa, UH-1 Iroquois, and UH-60 Black Hawk -- flew 86 percent of the 16.9 million flight hours flown by U.S. Army rotary-wing aircraft during the study period, 1 October 1979 through 30 September 1991. When stratified by helicopter type, the mishap rates for Class A or B ground-strike crashes (see Kleinbaum, Kupper, and Morgenstern, 1982, for discussion of rates) for the period were 4.83, 4.49, 3.65, 2.06, and 3.79 for the Cobra, Apache, Kiowa, Iroquois, and Black Hawk, respectively (Table 2). In this analysis, the mishap rates were analogous to incidence rates and the terms will be used interchangeably (Miettinen, 1976). Differences in ground-strike mishap risk among helicopter types were tested and the ground-strike mishap risk for the UH-1 Iroquois found to be significantly lower than other helicopter types. Attack helicopters (AH-64 Apache and AH-1 Cobra series) had the highest ground-strike mishap risk, significantly higher than either the OH-58 Kiowa or the UH-60 Black Hawk.

Table 2.

Standardized ground-strike mishap risk for selected U.S. Army rotary-wing aircraft: 1 October 1979 through 30 September 1991.

Helicopter type	Flight hours	Ground-strike mishaps	Ground-strike mishaps/100,000 hrs
Cobra	1,469,410	71	4.831
Apache	334,841	15	4.491
Kiowa	3,423,933	125	3.650
Iroquois	8,411,301	173	2.057
Black Hawk	1,267,648	48	3.786

Traditionally, risk comparisons are based upon periods of exposure, usually expressed as units of time. However, to date, the U.S. Army has not maintained a central repository of aircrew flight hours. Over the 12-year study period, over 96 percent of the helicopters examined had two crewmembers within the cockpit during the mishap. All Cobra, Apache, and Black Hawk series helicopters had two crewmembers within the cockpit at the time of the crash. In the Iroquois, 98.6 percent of the helicopters had two crewmembers within the cockpit area. The Kiowa, a single pilot helicopter, had the lowest percentage of aircraft with two crewmembers within the cockpit area, 91.46 percent. These

findings suggest injury risk estimates, based solely on helicopter flight hours, would be approximately twice the risk estimate based on crew flight hours.

An estimate of injury risk, based on helicopter flight hours, is presented in Table 3. Three risk estimates -- fatal, fatal + major, and fatal + major + minor injury -- are presented for the five helicopter types in the study.

Table 3.

Risk of cockpit crew injury per 100,000 flight hours: 1 October 1979 through 30 September 1991.

Helicopter type	Flight hours	Fatal injury		Fatal+major injury		Fatal+ major+minor injury	
		N	Risk	N	Risk	N	Risk
Cobra	1,469,410	31	2.109*	33	2.246*	72	4.900*
Apache	334,841	6	1.792*	8	2.389*	21	6.272*
Kiowa	3,423,933	37	1.081	49	1.431*	146	4.264*
Iroquois	8,411,301	59	0.701	66	0.785	192	2.283
Black Hawk	1,267,648	30	2.367*	37	2.918*	69	5.440*

*RR significant, $\alpha \leq .05$

Comparing the UH-1 Iroquois and UH-60 Black Hawk, both side-by-side seat, utility helicopters, the relative risk (RR) of fatality for the Black Hawk is 3.38.

$$(RR = Risk_{Black\ Hawk} \ / \ Risk_{Iroquois} = {}^{2.367}/_{0.701} = 3.3766)$$

The relative risk of fatality, comparing the Cobra with the Iroquois is 3.0086.

$$(RR = Risk_{Cobra} \ / \ Risk_{Iroquois} = {}^{2.109}/_{0.701} = 3.0086)$$

It has been suggested that time may be a potential confounder. Helicopter procurement, flight hours, and types of mission are correlated with fiscal year. However, our study did not support the hypothesis that injury risk is correlated with fiscal year. On the other hand, the results shown in Table 4 did not disprove the theory that changes in helicopter mix might influence crewmember injury. Further, newer helicopters do not

guarantee fewer mishaps since the correlation of time since introduction with conventional mishap risk was nonsignificant. Furthermore, the adjustment for fiscal year and years since introduction did not affect the injury risk. Thus, the findings indicate the association between mishap kinematics and the injury risk is not mediated through factors associated with fiscal year.

Table 4.

Distribution of injuries among cockpit crewmembers resulting from ground-strike mishaps, 1 October 1979 through 30 September 1991.

Fiscal year	Number of crewmembers	Fatal injury (I_1)	Major injury (I_2)	Minor injury (I_3)
80	60	13 (21.7%)	2 (2.3%)	21 (35.0%)
81	93	13 (14.0%)	0 ( )	33 (35.5%)
82	24	19 (15.3%)	2 (1.6%)	49 (39.5%)
83	76	07 (9.2%)	0 ( )	48 (63.2%)
84	63	16 (25.4%)	1 (1.6%)	22 (34.9%)
85	72	14 (19.4%)	5 (6.9%)	26 (36.1%)
86	72	15 (20.8%)	4 (5.6%)	24 (33.3%)
87	70	11 (15.7%)	4 (5.7%)	22 (33.3%)
88	58	12 (20.7%)	7 (12.1%)	17 (29.3%)
89	57	16 (28.1%)	3 (5.3%)	15 (26.3%)
90	56	12 (21.4%)	2 (3.6%)	15 (26.8%)
91	52	15 (28.9%)	0 ( )	15 (28.9%)
Overall	853	163 (19.1%)	30 (3.5%)	307 (36.0%)

Studywide, 19.1 percent of crewmembers involved in crashes were killed, an additional 3.5 percent had major, but nonfatal injuries, 36.0 percent suffered only minor injuries, while 41.4 percent escaped injury.

Modeling mortality

There are many factors that may influence the risk of injury for crewmembers during a crash. As discussed earlier, these include helicopter specific design parameters as well as dynamic and terrain factors. Table 5 examines selected dynamic and terrain factors, comparing the distribution of each (i.e., vertical velocity, ground speed, roll angle, pitch angle, yaw angle, terrain at primary impact, and flight duration) for the five helicopter types. Means were compared by multiple-stage testing using the Tukey-Kramer method.

Apache and Black Hawk helicopters were observed to have significantly higher vertical velocities at primary impact than Cobra, Iroquois, or Kiowa helicopters. Differences in ground speed (horizonal velocity) were not as striking, although Black Hawks did have significantly higher ground speed at major impact than other helicopter types.

In the next stage of analysis, multiple logistic regression was used to evaluate the association between injury, crash kinematics, and helicopter design standards. Logistic regression is a generalized linear model with the response equal to the proportion I/N, where I is the number of injuries and N is the population at risk. The probability distribution is binomial and the linking function is logit (Breslow, 1980). Confidence intervals for the binomial parameter, ρ, were computed based on the log likelihood function. In all cases, an event (fatality) was coded as 1 and no event (nonfatal) was coded as zero.

In most elementary terms, a crude (unconditional) rate is simply the total number of empirical cases (C) divided by the number of people in the population (P), or R = C/P. When two or more populations are compared, we then can speak of rate ratios ($RR=R_0/R_1$) or rate differences ($RD=R_0-R_1$). One drawback to comparing "crude rates" is the underlying structure of the populations being compared may be vastly different. When this happens, comparisons reflect not only differences in risks, but also differences in population structure. If we hypothesize equivalent populations, then we can speak of a standardized or conditional (because they are conditional on a hypothesized population structure) rates, and thus rate ratios and rate differences. While there are several approaches which can be used for epidemiological data analysis including the commonly used stratified null chi square (Mantel-Haenszel statistic), we will employ the multiple logistic (logit) regression approach (Cox, 1970). Not only does the logit represent a widely available approach, but also, it is intuitively more attractive since it is applicable to examining the relative importance of various crash components.

Table 5.

Means (and standard deviations) of selected variables, by helicopter type, for ground-strike mishaps, 1 October 1979 through 30 September 1991.

Variable	Helicopter series				
	Apache	Black Hawk	Cobra	Iroquois	Kiowa
Vertical velocity (ft/s)	28.4* (23.45)	41.4* (41.11)	18.2 (24.97)	15.4 (19.83)	15.1 (17.98)
Horizontal velocity (ft/s)	27.7 (33.95)	46.4* (56.86)	31.3 (49.19)	28.1 (37.37)	32.7 (45.48)
Roll (in degrees) (absolute value)	17.7 (31.08)	29.9* (49.70)	21.3 (35.95)	17.85 (31.98)	17.7 (30.10)
Pitch (degrees)	-9.0 (23.41)	-9.8 (47.12)	-5.5 (28.33)	-0.18 (25.52)	-5.7 (27.17)
Yaw (degrees)	10.3 (40.59)	16.7* (51.91)	13.1 (47.18)	6.10 (52.10)	4.6 (46.52)
Planned flight duration (min.)	18.3 (10.36)	26.0 (19.39)	20.7 (14.77)	19.4 (18.12)	21.1 (13.51)
Level impact site (percent)	47.3	60.4	56.6	58.8	51.6
Water impact (percent)	0	3.92	1.27	3.19	1.48

*Significant α = .05 (Tukey-Kramer method)

The logit function was first defined by Cornfield, 1962. The simplist form of the logit is

$$\hat{Y}=1/[1+e^{-(\beta 0+\beta 1X)}] \qquad (10)$$

where $\hat{Y}$ is the weighted estimate of the risk based on the intercept, β_0, plus the product of the statistical weight, β_1, and the variable, X. If X is a binomial, such as attack helicopter, where yes=1 and no=0, then $\hat{Y}$ is the equivalent of the unconditional relative risk for attack helicopters versus all other helicopters. Since we know there are differences in mishaps which are related to helicopter type, we adjusted for specific covariates.

Our choice of covariates was based on experience. We included design, kinematic, and terrain parameters as well as parameters which were specific to the individual crewmember. These included variables representing vertical velocity, ground speed, roll, pitch, yaw, terrain characteristics, as well as the age, sex, sitting height, stature, and crew position. In addition, mishap specific parameters such as wire-strikes, mission type, flight duration, and intrusion of external objects were included, where possible.

To simplify modeling, the five helicopter series were recoded into a single binomial variable. AH-1 Cobra, OH-58 Kiowa, and UH-1 Iroquois were coded as "precrashworthy (0)" because they were fielded before the U.S. Army crashworthiness design standards were implemented. The AH-64 Apache and UH-60 Black Hawk were coded as "crashworthy (1)" based on their introduction after the U.S. Army crashworthiness design standards were established. This grouping was reasonable based on differences in kinematic parameters shown in Table 5.

With precrashworthy and crashworthy aircraft identified, we systematically added covariates to our basic logistic model (10). After adjusting for vertical velocity (squared), ground speed (squared), roll (absolute value), and pitch, no other covariates were significant at α=0.90. Furthermore, none of the interaction terms between aircraft type (pre-/crashworthy) were found to be significant with either logit or linear analysis of variance. This lack of interaction (r>.20) suggests the effect of these covariates was similar in the two helicopter types, further justifying our original grouping.

In Table 6, odds ratios (OR) are presented, based on the maximum likelihood estimates of the β coefficients in Model 4 (Appendix A). As previously stated, the dependent variable, mortality, was coded as 1 if the crewmember was killed and 0 if the crewmember survived. After adjusting for vertical velocity, horizontal velocity, roll, and pitch, crashworthy helicopters had a lower crew mortality than precrashworthy helicopters (OR = 0.393, 95 percent CI 0.191, 0.8355). In other words, crewmembers in precrashworthy helicopters were 2.5 times more likely to be killed when compared to crewmembers in a crashworthy helicopter under similar impact conditions. Also, the odds of a fatal event increased as vertical and horizontal velocity increased. Interestingly, the most striking increase in the odds of mortality occurred when the helicopter struck the ground in an inverted position. With 180 degrees of roll, the odds of mortality was eight times that of the same mishap if the helicopter struck at zero degrees of roll.

Table 6.

Mortality odds ratios for specific kinematic parameters.

Independent variable		Odds ratio		95% Confidence limits	
Helicopter type		0.393		0.191	0.8355
Horizontal velocity (ft/s)	25	1.026		1.09	1.1555
	50	1.3912		1.179	1.3268
	75	5.8984		2.023	17.074
	100	8.0013		2.273	27.934
Roll (absolute value)	20	1.259		1.106	1.4324
	30	1.412		1.163	1.7144
	45	1.678		1.254	2.2447
	90	2.815		1.572	5.0386
	180	7.924		2.474	25.387
Pitch	-45	3.402		2.631	4.4015
	-15	2.290		1.303	3.7831
	-10	2.143		1.237	3.7143
	00	1.013		1.005	1.0218
	10	1.114		1.049	1.2405
	25	1.351		0.582	3.1343
Vertical velocity (ft/s)		Precrashworthy (0)		Crashworthy (1)	
		OR	95% CI	OR	95% CI
	30	2.789	2.218 3.509	1.116	0.887 1.403
	35	4.041	2.958 5.521	1.616	1.183 2.208
	40	6.197	4.122 9.316	2.478	1.648 3.725

In our final phase of modeling (model 5 in Appendix A), crashworthy helicopters were coded as having a vertical velocity design standard of 38 ft/s and precrashworthy helicopters were coded as having a design standard of 13 ft/s. These limits were based on the vertical velocity injury thresholds determined by Shanahan and Shannon (1993). β coefficients from the logistic model (Table 7) then were used to predict the impact of various vertical velocity design standards on crew mortality.

Table 7.

Final logistic model.

	β	STDERR	Wald χ^2	ρ
Intercept	3.3479	0.3384	97.875	0.0001
Standard	0.0373	0.0158	5.577	0.0182
$SQUARE_{vvel}$	-0.00103	0.000135	57.577	0.0001
$SQUARE_{hvel}$	-0.0002	0.000021	84.2746	0.0001
AROLL	-0.0130	0.00338	14.790	0.0001
PITCH	0.0227	0.00888	6.5141	0.0107
K_PITCH	-0.9803	0.3368	8.4713	0.0036

As our final comparison, we fitted the β coefficients in Table 7 to the actual kinematic data from the ASMIS database. For each mishap, values of 13, 16, 20, 24, 32, 38, 40, and 42 ft/s were substituted for vertical velocity design standard. The mortality probabilities for each value of design standard then were summed across all mishaps to determine our best estimate of the effect of crashworthiness standards given the kinematic differences among helicopter series. Where possible, we compared the model mortality estimates with the actual mortality for that helicopter series.

Table 8 presents the observed and predicted numbers of fatal events according to the helicopter type. One must remember that these are mortality estimates, and that estimates denote some degree of uncertainty. Prior to presenting this table, we presented point estimates in our tables with confidence intervals, which are actually estimates of the range of possible values for that estimate based on a 95 percent level of confidence. To simplify Table 8, we did not include any confidence intervals for the mortality estimates.

Table 8.

Estimated mortality based on final logistic model fitted to the kinematic parameters from the ASMIS database for FY 80-91.

Cockpit crewmember mortality		Helicopter series				
		Cobra	Apache	Kiowa	Iroquois	Black Hawk
Actual		31.0	6.0	37.0	59.0	30.0
Predicted: Based on final logistic model with vertical velocity design standard expressed in (ft/s)	13	31.7	7.3	40.8	58.2	37.8
	16	30.5	7.1	38.9	56.0	36.9
	20	29.0	6.7	36.5	54.8	35.6
	24	27.6	6.3	34.3	51.1	34.4
	32	24.9	5.8	31.2	44.2	32.3
	38	23.2	5.4	27.4	36.3	30.2
	40	22.6	5.3	26.6	35.1	29.6
	42	22.0	5.2	25.7	34.0	28.8

Table 8 is interpreted as follows: Based on our final logistic model and the kinematic estimates for the AH-1 Cobra mishaps, we predicted 31.7 deaths in a helicopter with a 13 ft/s vertical velocity design standard, 30.5 deaths in a helicopter with a 16 ft/s vertical velocity design standard, 29.0 deaths in a helicopter with a 20 ft/s vertical velocity design standard and so on. Actually, 31 deaths occurred in the AH-1 Cobra, a 13 ft/s design standard helicopter. Similarly, based on the kinematic parameters observed in the AH-64 Apache ground-strike mishaps, we predicted 7.3, 7.1, 6.7, 6.3, 5.8, 5.4, 5.3, and 5.2 deaths in helicopter with the 13, 16, 20, 24, 32, 38, 40, and 42 ft/s standards. Based on the Apache's design standard of 42 ft/s in the vertical axis, our predictions match the actual number of persons killed (5.2 predicted versus 6.0 actual) quite well. Predicted mortality for the Kiowa, Iroquois, and Black Hawk helicopters are interpreted in the same manner.

Seeking a second way to compare mortality, we contrasted the predicted mortality for crashworthy (Apache and Black Hawk series) and precrashworthy (Cobra, Iroquois, and Kiowa series) helicopters. Given the kinematic estimates of the Cobra, Iroquois, and Kiowa, we estimated if these helicopters were designed to a 20 ft/s vertical impact velocity, 11.2 lives would

have been saved since 1979 in crashes of these helicopters. Likewise, given the kinematics observed in the Apache and Black Hawk mishaps since 1979, if these helicopters had been designed to a meet a 13 ft/s standard, an additional 9.7 crewmembers would have been killed in mishaps involving these helicopters (Table 9).

Table 9.

Changes in estimated mortality resulting from modifying vertical velocity design criteria, 1 October 1979 through 30 September 1991.

Current helicopter design standards:	Model vertical velocity design criteria (ft/s)					
	13	16	20	24	32	38
1. Pre-crashworthy	NA	-5.3	-11.2	-17.7	-30.4	-43.9
2. Crashworthy	+9.7	+8.4	+6.7	+5.3	+2.5	NA

To this point, mortality estimates have been presented for the 11-year study period using historical flight hour data. To be useful for planning purposes, projections should be based on expected service life of a helicopter and projected flight hours with mortality estimates presented on an annual or service life basis. The following examples demonstrate the utilization of the model toward making these projections:

Application of model to existing helicopters

Currently, the Black Hawk contributes about 180,000 flight hours annually to the U.S. Army total. Based on an estimate of 240 flight hours per helicopter per year and a fleet of 1200 helicopters, we expect the total flight hours to rise to about 288,000 flight hours annually, as procurement of the Black Hawk is completed. Given a design life-expectancy of the Black Hawk of 25 years, we would expect the mortality for the Black Hawk to be:

Mortality (Black $Hawk_{N}$) =

Historical mortality risk * (annual flight hours/100,000) * 25

Historically, the risk of mortality for the Black Hawk has been 2.367 per 100,000 flight hours (Table 3). Thus, we would estimate the mortality for the Black Hawk over its design life of 25 years would be:

$$\text{Mortality(Black Hawk}_{38}) = 2.367*(288{,}000/100{,}000)*25 = \qquad 170.42$$

Based on the mortality estimates found in Table 8, we predict the corresponding mortality risk for a helicopter, like the Black Hawk but designed to a 32 ft/s vertical velocity standard, would be 2.548 per 100,000 flight hours (32.3 deaths/1,267,648 hours x 100,000 hours). Therefore, the mortality over the 25-year life of this 32 ft/s Black Hawk design would be:

$$\text{Mortality(Black Hawk}_{32}) = 2.548*(288{,}000/100{,}000)*25 = \qquad 183.46$$

The impact of decreasing the crashworthiness of a helicopter with flight characteristics of a Black Hawk from 38 to 32 ft/s would be:

$$\text{Mortality change} =$$

$$\text{Mortality(Black Hawk}_{32}) - \text{Mortality(Black Hawk}_{38}) =$$

$$183.46 - 170.42 = \qquad 13.04$$

Therefore, we estimate that 13 additional crewmembers would have been killed in the Black Hawk series if the vertical velocity design limit were 32 ft/s instead of 38 ft/s.

Application of model to developmental helicopters

The model we have proposed can be applied to developmental helicopters. As an example, if procurement is completed, the RAH-66 Comanche will represent the first of a new generation rotary-wing aircraft to be acquired by the U.S. Army. While the future of the RAH-66 is clouded at present, original plans call for procurement of up to 1,200 helicopters.

Our best estimate of the risk for morbidity and mortality of RAH-66 crewmembers is derived from historical data from the UH-60 Black Hawk and AH-64 Apache. Several factors suggest this is a fairly reasonable assumption. First, the UH-60 Black Hawk and the AH-64 Apache were designed to similar crashworthiness standards. Second, independent studies have shown these two helicopters exhibit essentially the same dynamic (kinematic) behavior during a crash that is quite different from older generation helicopters (Shanahan and Shanahan, 1989a). Third, based on such factors as mission, performance, and aerodynamic design, we postulate the RAH-66 Comanche will exhibit crash kinematics very similar to the UH-60 Black Hawk and AH-64 Apache,

and injury behavior similar to the AH-64 Apache, also a tandem seating attack helicopter. Finally, the procurement schedule of the RAH-66 Comanche will be similar to that of the UH-60 Black Hawk in terms of total number and phase-in and phase-out schedules.

Ideally, one would estimate the relative risk of crewmember injury for the RAH-66 using the distribution of injury observed in AH-64 crashes as a model. Unfortunately, since the AH-64 is relatively new, there is insufficient crash data in the ASMIS database to permit our developing a valid model. However, as discussed above, UH-60 data can be used to characterize the injury risk for RAH-66 crewmembers for the purpose of this analysis. If 1292 RAH-66 helicopters were procured and each helicopter accrued 240 hours per year during a 25-year life expectancy, then the Comanche design would accrue over 7.7 million flight hours during its design life. Based on this estimate and the assumption that the Comanche was built to the same vertical velocity impact standard (38 ft/s) as the UH-60 Black Hawk, we estimate crashes of the Comanche would generate 7.3 deaths per year, or 183.49 deaths over a design life of 25 years.

$$\text{Mortality } (\text{Comanche}_{38}) =$$

$$2.367(310{,}080/100{,}000)*25 = \qquad 183.49$$

However, if the vertical velocity crashworthiness standard was decreased to 32 ft/s as has been recently proposed, we estimate the helicopter would generate 7.9 deaths per year or 197.52 deaths over its design life.

$$\text{Mortality } (\text{Comanche}_{32}) =$$

$$2.548*(310{,}080/100{,}000)*25 = \qquad 197.52$$

This translates into 14.03 additional deaths, a 7.7 percent increase in mortality (14.03/183.49 = 0.0765) over the life cycle of the helicopter, for a 6-ft/s reduction in vertical velocity impact standard. Similarly, we predict a concomitant increase in major and minor injury, resulting in an overall increase in the likelihood of injury. Although a 6-ft/s reduction in the vertical velocity standard appears to be trivial, the reduction from 38 ft/s to 32 ft/s actually represents a 29 percent reduction in the total energy-handling capability of the airframe. Since injury is related to the kinetic energy applied to occupants in a crash, it is reasonable to anticipate substantially increased injury rates when the energy-attenuating capability of an airframe is reduced by almost one-third.

Furthermore, the estimate we provided probably is quite conservative for two important reasons. First, attack helicopters traditionally have a higher crash rate than utility helicopters, and we based our projection on crash data of a utility helicopter. Second, and more important, the Comanche will have retractable landing gear and a significant portion of its crashes will occur in the gear-up condition. Since the landing gear absorbs a considerable amount of the total energy in a vertical crash, we anticipate a significantly higher injury rate for crashes occurring with the gear up. Based on these factors, it is likely the Comanche will have a mortality rate anywhere from 20 to 50 percent higher than we have estimated.

Discussion

As with all models, there are certain restrictions on the use of this one. Two already have been discussed: potentially nonestimable parameters and possible biases from missing data. A third effects generalization from the sample to the general population. To make such generalizations, estimates must be based on sample data. ASMIS data is not a random sample. A fourth restriction involves the threshold covariate. It appears it may be difficult to specify a relationship between the marginal distribution and the threshold covariate and it is not clear to us how this problem should be solved. Finally, an important restriction arises from the interpretation of goodness-of-fit tests, such as the likelihood ratio tests. While logistic regression modeling has become a popular tool to explore injury data, there is in general no one-to-one relationship between the conditional distributions in the model.

A major advantage of the logistic approach is its flexibility and ease of application. The flexibility stems from the fact that the model can be used for continuous and discrete data. The ease of use stems from the wide range of statistical packages that include logistic regression as part of the available statistical analyses.

In this study, we focused on cases with death as the end point, since death represents a well-defined injury endpoint. The logistic was chosen as a descriptor of the data, not a model for the biological and mechanical processes underlying injury and its variation in degree. In other studies, however, information about the biological and mechanical processes underlying an event may direct the choice of a model for the marginal distribution. For example, it is possible to define an intermediate stage, major injury, consisting of crewmembers who suffer major but not fatal injury. Transition from no injury, to minor injury, to major injury, and finally to death is not certain owing to the effect of unmeasured covariates. Thus, a probability model for

injury for the sequence no injury, minor injury, major injury, to death should include three stages of transition. Our efforts now focus on extending the model to reflect this sequence and to include the competing risk of injury due to structural factors.

We showed that improvements in helicopter designs are associated significantly with crew survival. When decreasing mortality, it has been suggested that more disabling injuries will occur since more severely injured pilots will survive. Again, in the present study, relatively few crewmembers suffered major injuries: only 30 of the 546 injuries were classified as major. The limited number of major (I_2) injuries limited our ability to model major injury (I_2) alone. However, analyses were undertaken with major injury combined with mortality. Stepwise logistic regression, using SAS® LOGISTIC, was used to define new likelihood functions for death or survival with major injury. The implications of these analyses remain to be further explored, but the data did not show that survivors in more crashworthy helicopters were more likely to suffer major, disabling injury.

Although the logistic model proposed in this paper is based on multiple assumptions, we believe it reasonably predicts injury outcomes for defined crashworthiness design standards. Here, the vertical velocity design standard was used as the dependent variable because it is the best kinematic predictor of injury in helicopter crashes (Shanahan and Shanahan, 1989a). The model could be adapted to other dependent variables as needs arise.

This model provides program managers a highly useful tool for predicting the consequences of design tradeoff decisions in very real terms before any particular helicopter design is finalized. The use of more credible injury estimates will increase the weight of safety issues in tradeoff decisions by providing a counterbalancing force to the more readily determined and, frequently more persuasive, increase in procurement costs that the incorporation of safety features usually entails.

References

Aircraft crash survival design guide. 1989. Fort Eustis: Aviation Applied Technology Directorate, U.S. Army Aviation Research and Technology Activity (AVSCOM).

Breslow, N.E., and Day, N.E. 1980. Statistical methods in cancer research. Vol I. Lyon: IARC scientific publications.

Cox, D. R. 1970. The Analysis of Binary Data. New York: Halsted Press.

Cornfield, J. 1962. Joint dependence of the risk of coronary heart disease on serum cholesterol and systolic blood pressure: a discriminant function analysis. Federal Proceedings. 21:58-61.

Department of Defense. 1988. Light fixed- and rotary-wing aircraft crash resistance. Washington, DC: Department of Defense. MIL-STD-1290(AV). 26 September.

Department of the Army. 1980. Accident reporting and records. Washington, DC: Department of the Army. AR 385-40.

Donaldson, J. R., and Schnabel, R. B. 1987. Computational experiences with confidence regions and confidence intervals in nonlinear least squares. Technometrics. 29:67-82.

Draper, N., and Smith, H. 1966. Applied regression analysis. New York: John Wiley.

Fleiss, J. L. 1979. Confidence intervals for the odds ratio in case-control studies: the state of the art. Journal of chronic disease. 32:69-77.

Haley, J. R., Jr. 1992. Personal communication. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. March 1992.

Hosmer, D. W., and Lemeshow, S. 1989. Applied logistic regression. New York: John Wiley and Sons.

Kalbfleisch, J. D., and Street, J. O. 1990. Survival analysis. In: Berry, D. A. Statistical methodology in the pharmaceutical sciences. New York: Marcel Dekker, Inc.

Kleinbaum, D. G., Kupper, L. L., and Morgenstern, H. 1982. Epidemiologic research: Principles and quantitative methods. New York: Van Nostrand Reinhold.

Mehta, C. R., Patel, N. R., and Gray, R. 1985. Computing an exact confidence interval for the common odds ratio in a series of 2x2 tables. Journal of the American statistical association. 86:404.

Miettinen, O. S. 1976. Stratification by multivariate confounder score. American journal of epidemiology. 104:609-620.

SAS® Institute, Inc. 1990. SAS® statistics. Cary, NC: vol. 604.

Shanahan, D. F., and Shanahan, M. O. 1989a. Kinematics of U.S. Army helicopter crashes, 1979-1985. Aviation, space, and environmental medicine. Vol 60, pp.12-21. February.

Shanahan, D. F., and Shanahan, M. O. 1989b. Injury in U.S. Army helicopter crashes, September 1979 through October 1985. Journal of trauma. April.

Shanahan, D. F., and Shannon, S. G. 1993. Estimating the injury threshold for U.S. Army rotary-wing aircraft. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. In press.

Appendix A.

Model fitting.

The nature of helicopter accidents provides a natural experiment comparing the effect of improvements in the design and manufacture of rotary-wing aircraft. The outcome of each mishap is the presence or absence of injury in a crewmember. While these data do not lend themselves well to the traditional linear model, a generalized linear model can be used to form maximum likelihood estimates of the parameters through an iterative fitting process. As in the case of traditional linear regression, statistical inferences can be made from fitted generalized linear models using confidence intervals and hypothesis testing.

To construct a generalized linear model, an appropriate linking function and response probability distribution must be specified. The strategy for selecting an appropriate linking function and response distribution begins by examining the response and explanatory variables in the ASMIS database. While our selection of linking functions was limitless, we limited our choices to those linking functions available in our statistical software. As both Logistic and Poisson regression are available in SAS® release 6.08, we will limit our discussion to these procedures.

Both procedures were appropriate for our response and explanatory variables. Polynomial Poisson regression traditionally has been used to model the distribution of cell counts in a multiway contingency table, while multiple Logistic regression has long been used to model an effect where the outcome is a proportion. Our final choice of statistical method, as well as our choice of model, was decided by the effective sample size. Both Poisson and Logistic methods require that the sample size be sufficiently large to support the asymptotic distribution of the response function. As a general guideline, Poisson regression requires that each contingency table have an effective sample size of at least 25. In logistic regression, the data must be dispersed so that no more than 20 percent of the response functions have an effective sample size less than five. Thus the sample size must be at least 100 to support four levels of response in Poisson regression modeling while a sample size of 30 could be sufficient to support the same number of response functions in logistic regression, provided that the functions were the means of four dependent variables (SAS, 1989). As crashworthy helicopters are relatively new, our effective sample sizes were inadequate for polynomial Poisson regression, thus logistic regression was used for multivariate modeling.

In all logistic analysis, the response variable is the binomial proportion Y = events/trials. If the independent variables in the analysis are treated quantitatively, then the logistic analysis is known as logistic regression.

The logit, or logistic function (first defined by Cornfield in 1962) has the form $\eta=\log(\mu/(1-\mu))$. If we fit a binomial model with only an intercept term β using the logit link function then the estimated binomial probability ρ and the estimated mean β are $\beta = \text{logit}(\rho)=\log(\rho/1-\rho)$ and $\rho=\exp\beta/(1+\exp\beta)$.

In our regression model the estimated mean β corresponds to:

$$\beta= \beta_0+\beta_1x+\beta_2y+\beta_3z \tag{1}$$

where β is the sum of the products of the maximum likelihood estimate and the independent variable. In our model the independent variables were: helicopter type, vertical velocity change, horizonal velocity change, pitch angle, and roll angle. The uncorrelated error, ϵ, with a mean of zero and a constant variance is implied in all models.

In our modeling, computational difficulties occurred when large numbers of unique values were included in the logistic model. For this reason, continuous variables were recoded when possible. For example, horizonal velocity change, a continuous variable, was recoded into five ft/s intervals thereby reducing the number of unique values, and thus degrees of freedom in the model.

In order to fit our logistic model the five helicopter types were recoded into a single dichotomous (0,1) predictor variable. The β coefficient for this dichotomous variable, obtained from the multiple logistic modeling, was then back-transformed to obtain an estimate of the likelihood of sustaining a specific degree of injury in a crashworthy helicopter (Apache, Black Hawk), all other factors being held constant. The helicopter coding scheme was:

Helicopter series		AC_TYPE
1	Iroquois, Cobra, Kiowa	0
2	Apache, Black Hawk	1

The estimated probability of injury (ρ) in a specific helicopter mishap can be obtained by back-transforming the logistic function. If we incorporated all of the kinematic

parameters in our logistic model then $\rho = 1/[1 + \exp^{-(\beta 0 + \beta 1s + \beta 2t + \beta 3u + \beta 4v)}]$. Conversely, the estimated probability of no injury would be $1-\rho$ and,

$$1-\rho = 1-[1/(1+e^{-(\beta 0+\beta 1s+\beta 2t+\beta 3u+\beta 4v)})] =$$

$$[[1+e^{-(\beta 0+\beta 1s+\beta 2t+\beta 3u+\beta 4v)}]/[1+e^{-(\beta 0+\beta 1s+\beta 2t+\beta 3u+\beta 4v)}]]-[1/[1+e^{-(\beta 0+\beta 1s+\beta 2t+\beta 3u+\beta 4v)}]] =$$

$$e^{-(\beta 0+\beta 1s+\beta 2t+\beta 3u+\beta 4v)}/[1+e^{-(\beta 0+\beta 1s+\beta 2t+\beta 3u+\beta 4v)}]$$

Thus the natural logarithm of the odds ratio is always adjusted for linear relationships in the statistical model.

In linear regression, the distribution of β and the level of tests and the confidence regions are known exactly. This is not so in nonlinear regression, where it is necessary to rely on approximations. While there are several ways to construct such approximations, we used the Wald χ^2 procedure.

Our strategy for selecting a best model was to fit a sequence of models, beginning with a simple model containing a single variable, and then adding or deleting explanatory variables in each successive model. Our initial logistic regression model contained only helicopter type while the later models contained vertical and horizonal velocity, and the pitch angle at primary impact in addition to helicopter type. The output of this model, shown below, provides the estimates of the β coefficients from the Type 3 analysis. This is analogous to the Type III sums of squares in a linear regression model.

First logistic model.

	β	STDERR	Wald χ^2	ρ
Intercept	3.1749	0.1893	281.217	0.001
AC_TYPE	0.869	0.3667	4.842	0.0278
$SQUARE_{vvel}$	-0.00122	0.000129	90.145	0.0001
$SQUARE_{hvel}$	-0.00013	0.00001	68.164	0.0001
PITCH	0.0160	0.00362	19.478	0.0001

The positive value for the AC_TYPE slope change ($\beta = 0.869$) shown in Model 1 suggests the incidence rate increase more slowly for a given increase in other kinematic parameters for crash-worthy (Black Hawk and Apache) than precrashworthy helicopters. The negative values for change in vertical and horizontal

velocity slope suggests that, controlling for all other factors, injury rates increase with velocity change, particularly with changes in vertical velocity.

Haley (1992) suggested injury tolerance to impact forces might depend on individual crewmember characteristics such as age, statutory height, body mass (weight), race, and/or sex. However, in our modeling no significant effect was seen for any demographic characteristic regardless of grouping. It may be that military personnel generally are more homogeneous with respect to demographic and anthropometric variables than the general population. In any case, all demographic and anthropometric variables were dropped in subsequent analyses, essentially treating all crewmembers the same. There were two reasons for this decision, (1) it simplified the model and (2) Donaldson and Schnabel (1987) reported that the TYPE 1 error rate increases with the number of parameters for the Wald χ^2 statistic in multiple-parameter simulations. Therefore, it seemed prudent to limit the number of variables in the model.

In our first tier of modeling, roll and yaw angle did not meet the 0.3 significance levels for entry into the model. These parameters were recoded to their absolute values, denoted as AROLL and AYAW, respectively. The second tier of injury modeling is shown as second logistic model.

Second logistic model.

	β	STDERR	Wald χ^2	ρ
Intercept	3.4299	0.2117	262.383	0.001
AC_TYPE	0.8725	0.3761	5.3818	0.0203
$SQUARE_{vvel}$	-0.00155	0.000135	72.1887	0.0001
$SQUARE_{lvel}$	-0.00013	0.000016	70.7277	0.0001
AROLL	-0.0119	0.00323	13.4637	0.0002
PITCH	0.0160	0.00363	19.4777	0.0001

In our second tier of analyses, no effects were seen for YAW or its absolute value, AYAW, regardless of the helicopter grouping. The absolute value of roll, AROLL, was statistically significant in this model, indeed subsequent modeling showed the effect of the absolute value of roll, AROLL, varied by helicopter type. The injury function derived from this second tier of modeling predicted the incident of injury would be slightly

higher for crewmembers in crashes of precrashworthy helicopters. The β coefficients for both AC_TYPE and $SQUARE_{vvd}$ increased slightly, denoting a change in slopes for these variables.

In the third tier of modeling, we tested the effect of attack helicopters on the mortality risk. Attack helicopters (AH-1 and AH-64) were coded "1" while all other helicopters series were coded "0." The relative newness of the AH-64 series helicopters severely limited our ability to pursue these analyses. Many of our response levels contained only a single observation and most, if not all, response levels for crashworthy attack helicopters contained less that five observations. When dropped, the β coefficient for attack helicopters was 0.3938 with a resultant Wald χ^2 statistic p-value of 0.174. This equates to a 60 percent increase in the risk of mortality in attack helicopters after controlling for kinematic and design differences.

In our fourth tier of modeling, we tested the possibility of a threshold effect for our continuous variables. To determine if a threshold effect was present for roll, a dichotomous variable K_Roll was created. By default, K_ROLL was coded as "0" and was recoded to "1" only if the value of the roll exceeded the predetermined value, hence the term "threshold." For example, K_ROLL30 was equal to "1" if the absolute value of roll was greater than 30 degrees. As we increased the number of variables in our model, we soon reached a point where the effective sample size would not support any additional variables. At this point, we elected to recode continuous variables by using 10 ft/s intervals for velocity and 10 degrees intervals for all angles. This allowed us to model threshold values for all kinematic parameters.

In all, we modelled over 50 threshold values for roll, pitch, and horizontal velocity. Starting threshold values were selected based on the authors' experience investigating helicopter crashes. No threshold effect was found for roll when modeling ceased at a threshold value of 45 degrees. For pitch, the Wald χ^2 statistic in the type III analysis was first significant at threshold values of -15,+25 degrees. Likewise, for horizontal velocity, a threshold of 65 ft/s was identified in precrashworthy helicopter crashes versus 100 ft/s in crashworthy helicopters. These values were utilized as the thresholds for pitch and horizonal velocity in subsequent modeling.

The third model gives the parameter estimates and their standard errors for the fitted logistic function, including threshold values for pitch and the variable identifying attack helicopters. In this analysis, the threshold value for pitch was -15 to 25 degrees. Parameter values omitted from the model did

not differ significantly (ρ<0.10) from zero and have been equated to zero in calculating predicted injury.

The coefficient β = -.00103 for vertical velocity ($SQUARE_{vvel}$) specifies, on a log-log scale, the increase in incidence per foot of velocity-squared. The standard error for ATTACK suggests no statistically significant effect of attack helicopters was seen in these crashes. Probably this was because of the relatively small number of crashes involving crashworthy attack helicopters in our sample. No threshold was identified for ROLL at less than 45 degrees, and testing of thresholds greater than 45 degrees was not undertaken.

Third logistic model.

	β	STDERR	Wald χ^2	ρ
Intercept	3.8327	0.2633	211.92	0.0001
AC_TYPE	0.9324	0.3948	5.5771	0.0182
$SQUARE_{vvel}$	-0.00103	0.000135	57.5771	0.0001
$SQUARE_{hvel}$	-0.0002	0.000021	84.2746	0.0001
AROLL	-0.0130	0.00338	14.798	0.0001
PITCH	0.0227	0.0088	6.5141	0.0107
ATTACK	0.3938	0.3196	1.5188	0.174
K_PITCH	-0.3657	0.1950	3.5170	0.0607

At the next phase of analysis, two new variables were created. The first, STANDARD, was coded as 13 for precrashworthy helicopters and 38 for crashworthy helicopters. The second variable, H65, was the result of our earlier modeling of threshold values for horizonal velocity change and denotes ground speed greater than 65 ft/s. First, we entered H65 into the previous model:

Fourth logistic model.

	β	STDERR	Wald χ^2	ρ
Intercept	3.7054	0.2428	232.9069	0.001
AC_TYPE	0.9165	0.3759	5.9443	0.0148
$SQUARE_{vvel}$	-0.00114	0.000137	69.3015	0.0001
$SQUARE_{hvel}$	-0.00007	0.000022	11.5305	0.0007
H65	-1.3776	0.4183	10.8476	0.0010
AROLL	0.0115	0.00336	11.7674	0.0120
PITCH	0.0132	0.00426	9.5893	0.002
K_PITCH	-0.6306	0.323	3.9046	0.049

All variables in the fourth model were significant (α =.05). However, since K_PITCH had a ρ of .049, the score χ^2 statistic also was calculated for this model. As previously stated, Donaldson and Schnabel (1987) criticized the WALD χ^2 statistic for its tendency to fail to reject an invalid null hypotheses. In Donaldson and Schnabel's studies, the Wald χ^2 statistic always was within a few percentage points of the likelihood-based confidence intervals, considered by the authors to be the gold standard. Since the Wald χ^2 statistic ρ for K_PITCH was near the cutpoint of .05 (0.049), the score χ^2 statistic was calculated as a more sensitive test of the hypothesis. The score χ^2 statistic for K_PITCH was 4.10 with a ρ of less than .05, so K_PITCH was retained in the model.

Naturally, when we added variables to our model, we increased the number of cells. By adding H65 to model 3, we doubled the number of cells. Our overall sample size was inadequate for support of this number of cells, so we dropped H65 from our logistic modeling. When we dropped H65, the concordance of our model dropped only from 92.4 to 92.3, an insignificant amount.

As a final model, we substituted STANDARD for AC_TYPE. This model was identical to model 4 except a continuous variable, STANDARD, was substituted for the dichotomous variable AC_TYPE. STANDARD was defined as 13 ft/s for precrashworthy helicopters and 38 ft/s for crashworthy helicopters, based on the vertical velocity change estimates in the study by Shanahan and Shannon (1993).

In ground-strike mishaps, a pitch angle of less than -15 degrees or more than 25 degrees was associated with increased mortality in all helicopter types, as seen by the marked decrease in the slope of the incidence rate function within the pitch interval (ρ<0.01 in all five helicopter types). The size of the slope change is similar in precrashworthy and crashworthy helicopters and agrees well with that noted by Shanahan and Shanahan (1989a).

Goodness of fit testing did not indicate any inadequacy in the fifth logistic model. The test of association of predicted probabilities and observed responses were: Somer's D statistic = 0.851, Gamma statistic = 0.855, and Tau-a = 0.263. Concordance was 92.3 percent, discordance was 7.2 percent, and 0.4 percent were tied. Sensitivity was 98.9 percent, specificity was 66.2 percent, and the percent correct were 97.2.

Fifth logistic model.

	β	STDERR	Wald χ^2	ρ
Intercept	3.3479	0.3384	97.875	0.0001
Standard	0.0373	0.0158	5.577	0.0148
$SQUARE_{vvel}$	-0.00103	0.000135	57.5771	0.0001
$SQUARE_{hvel}$	-0.0002	0.000021	84.2746	0.0001
AROLL	0.0130	0.00338	14.798	0.0001
PITCH	0.0227	0.00888	6.5141	0.0107
K_PITCH	-0.9803	0.3368	8.4713	0.036

This was the final logistic regression model developed, and it was used in the present study to predict the impact of the vertical velocity design standard on mortality.

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